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BORDER MONITORING BASED ON A NOVEL PIR DETECTION MODEL

by

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Improvements in technology have enabled the development of cost-effective, low-power, multifunctional wireless sensor nodes, which are used in various applications including surveillance and intrusion detection. We have made experiments in order to discover the detection probability of the Crossbow MSP410 mote sensor nodes. We have developed a new PIR detection model, which has a high probability detection region and a low probability detection region, for MSP410 mote sensor nodes based on the observed probabilities.

The PIR model is used in the proposed sensor placement strategy for MSP410 mote sensor nodes intended for a border monitoring scenario. The detection probability of the low probability region of the new PIR detection model is increased by overlapping with the low probability region of the neighboring sensor nodes in the proposed sensor placement strategy.

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BORDER MONITORING BASED ON A NOVEL PIR DETECTION MODEL

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I. INTRODUCTION

A. BACKGROUND

Improvements in technology have enabled the development of cost-effective, low-power, multifunctional wireless sensor nodes. Large numbers of these sensor nodes are used in Wireless Sensor Networks (WSN). WSN are becoming commonly used by government, military, business, and home users with various applications in many areas.

Surveillance and intrusion detection are common usage areas of WSN. The computational power and speed of today's computer systems enable the running of complex algorithms for surveillance and intrusion detection by using data obtained from wireless sensor nodes. Depending on the needs of the application, different power schemes can be implemented to improve the sensors' battery life. Power efficient sensor nodes may provide continuous coverage, depending on their deployment strategies, for many years.

Infrared (IR) technology is commonly used in surveillance and intrusion detection applications. Passive infrared (PIR) sensors are capable of detecting the movement of humans and vehicles by sensing the heat radiated by the target. Developments in PIR technology enable detection of object's movement with low false alarm rates. PIR sensors may provide reliable coverage in their sensing range.

B. PROBLEM STATEMENT

The first goal of this thesis is to contribute to the applications of the PIR motion detection technology by developing a PIR detection model in a probabilistic approach based on experimental evaluations for the Crossbow MSP410 mote sensor nodes.

The second and main goal of this thesis is to contribute to the WSN literature by proposing an efficient wireless sensor placement strategy based on a newly developed PIR detection model for the surveillance and intruder detection aspects of border monitoring applications using the CROSSBOW MSP410 mote sensor nodes.

C. OVERVIEW

Chapter II gives background information about Wireless Sensor Networks (WSN) and state-of-the-art PIR technology.

Chapter III introduces the Crossbow MSP410 PIR sensors used in surveillance and intrusion detection applications and examines the behavior of the PIR sensors in order to develop a sensor model based on experimental results. It analyzes experiment results in a probabilistic approach related to the sensing capabilities of the PIR sensors, which are affected by various factors.

Chapter IV gives information about possible wireless sensor deployment methods and wireless sensor placement strategies used in the WSN literature. It proposes an efficient wireless sensor placement strategy for the surveillance and intrusion detection aspects of border monitoring applications using the CROSSBOW MSP410 mote sensor nodes.

Chapter V discusses the conclusions and recommendations for future studies.

II. BACKGROUND

A. WIRELESS SENSOR NETWORKS

1. Introduction

Developments in wireless networking, micro-electromechanical system technology (MEMS), microprocessor technology, and digital electronics have enabled the design and development of low-cost, low-power, multifunctional sensors that can be used in large-scale Wireless Sensor Networks (WSN) for various commercial and military applications. WSN are used to gather information from the environment where they are deployed. The information that is gathered can be processed to monitor the environment in real-time or stored in a database for later processing, based on the needs of the application it is used for. Sensor nodes can be deployed in various ways for to maximize their efficiency in accordance with the requirements of the application.

The improvements in technology have allowed the development of sensors in very small sizes that are capable of sensing, performing computations, and communicating. A tiny sensor that is approximately the size of a quarter, produced by Crossbow Technology Inc., is shown in Figure 1. Advanced mesh networking protocols have enabled the use of large numbers of tiny sensor nodes together to set up a wireless sensor network.

Figure 1. Crossbow MICA2DOT Quarter-Size Sensor (from Ref. [1])

The MICA2DOT mote sensor shown in Figure 1 is used in temperature and environmental monitoring applications. The sensor node running TinyOS Distributed Software Operating System supports wireless remote reprogramming in order to minimize redeployment requirements. [1]

2. Applications

WSN applications are widely used in information collection and analysis in today's information systems. The applications can be categorized as military and commercial.

Some of the military WSN applications discussed in [2] are:

- Monitoring friendly forces, equipment, and ammunition
- Reconnaissance of opposing forces and terrain
- Surveillance at the battlefield
- Transmission of targeting information
- Assessment of the battle damage
- Nuclear, biological, and chemical attack detection and surveillance

Some of the commercial sector WSN applications discussed in [2] are:

- Tracking the movements of birds, small animals, and insects
- Field irrigation
- Monitoring environmental conditions that affect crops and livestock
- Fire detection in forests
- Biocomplexity mapping of the environment
- Flood detection
- Precision agriculture
- Telemonitoring of human physiological data
- Tracking and monitoring doctors and patients inside hospitals

- Drug administration in hospitals
- Home automation
- Smart environment design
- Environmental control in office buildings
- Interactive museums
- Detecting and monitoring car thefts
- Managing inventory control
- Vehicle tracking and detection
- Surveillance and intrusion detection

3. Challenges

WSN are an emerging and challenging area in today's information systems, and they are open to many research opportunities. Many studies have been done in order to increase efficiency in routing protocols, placement strategies, power conservation schemes, and secure transmission protocols. Researchers are still investigating these vital and problematic areas of WSN in accordance with application requirements.

Since the wireless sensor placement strategy is a very important factor that affects all aspects of WSN, most of the studies conducted on WSN concentrate on wireless sensor placement strategies. The optimization of sensor placement highly depends on applications and terrain information. Various placement strategies have been proposed for many specific remote sensing scenarios. However, because the sensing model used in the optimization of sensor placement affects the solutions, scientists commonly use the binary sensing model that is introduced in Chapter IV.

B. PASSIVE INFRARED TECHNOLOGY

The wavelength segment between the visible and the microwave segments in the electromagnetic spectrum is defined as infrared light. Infrared light is divided into regions based on the wavelength of the light. These regions are called “Near Infrared”, “Mid Infrared”, “Far Infrared”, and “Extreme Infrared”. The infrared regions are shown in Figure 2. The far infrared region is also known as the thermal waves region. The primary source of infrared radiation is heat or thermal radiation. Any object that has a temperature radiates in the infrared. Humans, at normal body temperature, radiate most strongly in the infrared at a wavelength of about 10 microns [3].

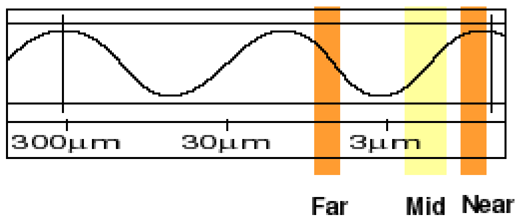

Figure 2. Infrared Region of the Electromagnetic Spectrum (from Ref. [3])

1. History

The heat radiated by human body can be detected by using infrared detectors. Since motion detectors do not emit any electro magnetic waves to sense the heat radiated by humans, this technique is called passive infrared (PIR). The basics of PIR technology evolved at Optical Coating Laboratory in California and at Barnes Engineering in Colorado. In 1970, Herbert Berman invented the segmented mirror made from metallized plastic as an effective system for the optical gain and the special modulation needed to generate a signal when people move across a field of view. The principal of special modulation is one of the basic elements of PIR [4].

PIR motion detectors use thermal sensors to detect the small temperature increase when a sensor element is exposed to radiation. A major breakthrough was achieved in 1979 with the commercial availability of dual pyroelectric sensors. The differential operation of the sensors compensates for the influences of wind, warm air, daylight, and other stimuli on the detector and reduces false alarms [4].

PIR motion detectors are commonly used as door openers, automatic light switches, which can help to save energy, and burglar alarm sensors. Since PIR motion detectors have a wide range of applications, there are many manufacturers in the market. Some of the leading brands in PIR sensor systems are Honeywell International, Crossbow Technology, ADT Security Systems, Detection Systems, KUBE Electronics, and Visonic.

2. Detection Model

The sensing elements of the sensor are divided into small regions in order to compare heat changes between neighboring sensing regions. Current PIR motion detector sensors use Fresnel lenses to focus radiated heat over the sensing elements of the sensors. Fresnel lenses help to increase the sensing range of the sensors. PIR motion detection technology allows reliable detection in low range applications by reducing the background effects.

Since environmental conditions affect the sensing capabilities of PIR motion detection sensors, sensing models are developed to simulate sensing behaviors of these sensors in scientific studies. The simplicity of the binary sensing model enabled widespread use of this sensing model in WSN studies. A probabilistic sensing model in which sensing isn’t guaranteed inside the coverage area can also be used in order to make the research closer to real conditions. We used a probabilistic approach to model the PIR sensing capability of the Crossbow MSP410 mote sensor nodes in this thesis.

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III. DEVELOPMENT OF A PIR SENSOR DETECTION MODEL

A. INTRODUCTION

We discussed wireless sensor networks and passive infrared in the previous chapter. In this chapter, we will give detailed information about the Crossbow MSP410 Mote Security System and its components. We will continue the discussion with our evaluation of experiments for the Crossbow MSP410 mote sensor nodes. We will try to develop a PIR Sensor Detection Model for MSP410 mote sensor nodes at the end of this chapter.

B. CROSSBOW MSP410 MOTE SECURITY SYSTEM

The MSP410 mote security system consists of eight MSP410 sensor nodes, one MBR410 base station, one MTS101 programming adapter board, and MOTEVIEW software. The mote security system can be used in such security applications as remote border security, perimeter protection, surveillance and intrusion detection, and building occupancy monitoring [5]. The Crossbow MSP410 mote security system is shown in Figure 3.

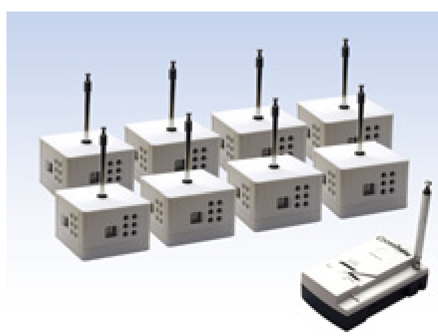

Figure 3. Crossbow MSP410 Mote Security System (from Ref. [6])

MSP410 sensor nodes are capable of magnetic field detection, PIR sensing, and audio sensing. The 2-axes magnetic field sensor can detect perturbations in the local magnetic field at distances up to 60 feet while using noise-filtering algorithms to minimize false-detections. This functionality of the sensor nodes is not used in this research. PIR sensors equipped with four separate sensing elements arranged orthogonally to provide 360-degree coverage can be used to detect dynamic changes in the local thermal radiation environment. Since each sensor is equipped with four PIR sensing elements, which enables the identification of initial object vector as well as subsequent movement and direction, it can only provide us 90-degree location information based on its detecting sensing element. This capability can allow us detection of humans and vehicles up to 80 feet or more in some cases. This thesis is concentrated on human detection applications.

The MSP410 mote security system runs an XMesh-enabled sensing application within its embedded modules. XMesh™ is an open, flexible, proven ad-hoc wireless mesh networking protocol stack developed by Crossbow Technologies.

The main hardware features of MSP410 sensor nodes are listed below:

- MICA™ Mote Technology running an XMesh™-enabled sensing application
- Quad PIR detector with IR transparent windows
- 2-Axis linear magnetic field detector
- Telescoping antenna with water resistant grommet seal
- On/Off switch
- Heat reflective plastic enclosure
- Two AA batteries
- Dimensions: 3.5'' x 3.5'' x 2.4'', not including the antenna

The sensor nodes are equipped with an Atmel Atmega128 microcontroller that controls all the functions of the sensor nodes. The Chipcon CC1000 radio is used for wireless communication. The radio uses a two-tone frequency shift keying (FSK) modulation technique to transmit and receive data. The radio can be changed to different frequencies depending on the limits of the frequency band. It is configured for the 433 MHZ band which allows at least 250 ft on flat areas, and 150 ft when placed on grassy terrain with rolling hills. The radio range is not a limiting factor for our research.

The Crossbow MSP410 mote sensor node is shown in Figure 4. The red area in Figure 4 shows the magnetic field detection sensing window. The cyan area in Figure 4 shows the PIR sensing system IR window.

Figure 4. Crossbow MSP410 Mote Sensor Node (from Ref. [7])

The mote sensor nodes PIR sensing subsystem is equipped with KUBE Cone Optics TR230 and KUBE C172 pyroelectric dual element sensors designed for detecting motion of a thermally radiating body. KUBE C172 consists of two physically separated pyroelectric sensing elements and a JFET amplifier sealed into standard hermetic metal TO-5 housing with an optical filter window. The sensing elements are connected electrically in a series opposed dual (SOD) configuration for common mode signal cancellation. Signals from radiation falling on both active areas simultaneously will be cancelled, whereas a defined beam passing from one element to the next element will produce one positive and one negative pulse while an object is moving [8]. KUBE TR230 is the housing for supporting optical integration to the C172 dual sensing element. KUBE C172 and KUBE TR230 are shown in Figure 5.

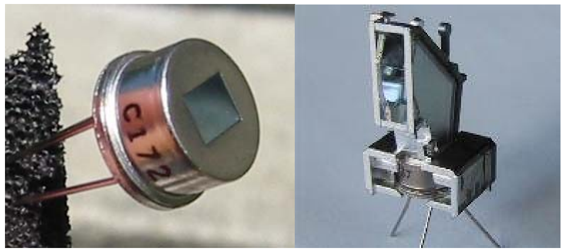

Figure 5. KUBE C172 and KUBE TR230 (from Ref. [8] , [9])

KUBE TR230 provides a 90-degree horizontal and 30-degree vertical field of view that enables a detection range of up to 15 meters. The top view of TR230 that shows the horizontal field of view and the side view of TR230 that shows the vertical field of view are shown in Figure 6. Detection ranges based on the sensitivity level of the sensor are given in Table 1.

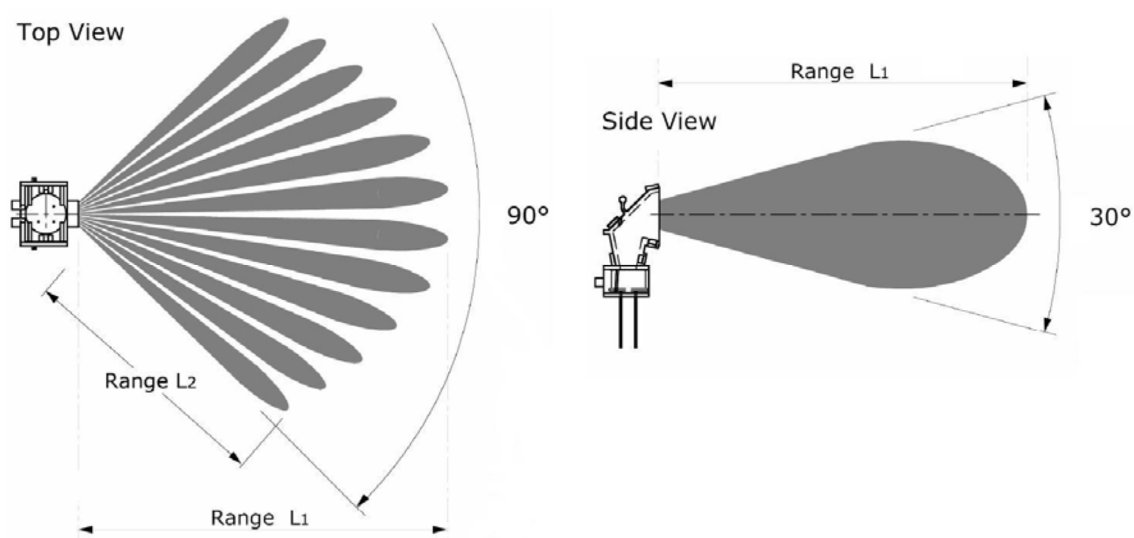

Figure 6. KUBE TR230 Top and Side Views (from Ref. [9])

Sensitivity	Range	
	L1	L2
Maximum	15 m	10 m
High	12 m	8 m
medium	9 m	6 m
Low	6 m	4 m
Very low	3 m	3 m

Table 1. KUBE TR230 Detection Ranges (from Ref. [9])

The sensing element generates pulses when a heat-radiating object moves from one area to another in the coverage window of the sensing element, as shown in Figure 7. Since the object needs to move from one area to another, it is possible that a steady body may not be detected by The MSP410 mote sensor node. Mote nodes may also be adversely affected by environmental conditions such as wind, background temperature, direct sunlight, and deployment terrain.

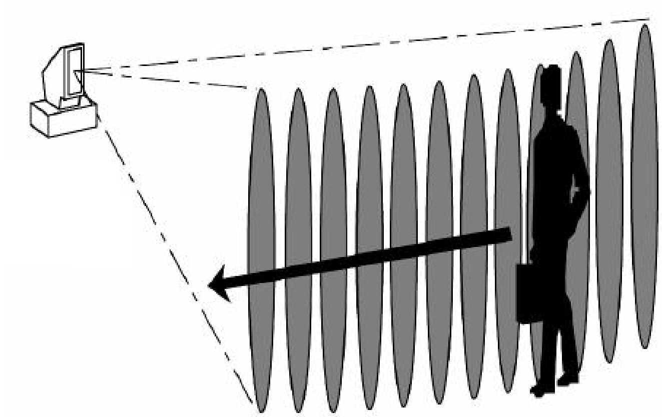

Figure 7. KUBE TR230 Movement Detection (from Ref. [9])

MoteView™ software collects data from mote sensor nodes via the MBR410 base station and stores the time stamped information in a database. The mote sensor node reports IR detection with PIR and Quad values. The mote sensor node calculates the Quad value based on its sensing elements that detect the motion of the target. Quad values give us position information about the target relative to mote sensor node. Possible Quad values and their coverage areas are shown in Figure 8.

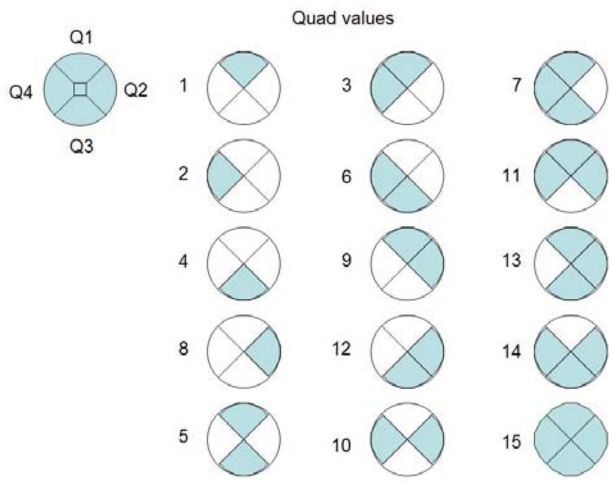

Figure 8. MSP410 Mote Sensor Node Quad Values

C. EXPERIMENTS WITH MSP410 MOTE SENSOR NODE

1. Description

The goal of the experiments is to investigate the behavior of the MSP410 mote sensor node for a given scenario in order to develop a PIR sensor model that will be used in generalization for sensor deployment strategies. PIR detection is a function of many variables such as speed, distance, temperature, wind, terrain, sensor height, and sensor battery level. Because of the many variables, we tried to design sensor-evaluation experiments compatible with its movement detection characteristics in order to measure its detection probability based on object speed and object distance from the sensor. We selected similar environmental conditions in order to minimize environmental effects on PIR sensors. We also turned on only one sensor in each experiment to minimize networking effects on the experiments.

We deployed one sensor in a baseball field at 50 cm from the ground and 15 m from the base station that was connected to the computer. As we discussed earlier, the MSP410 mote sensor warns detection if a heat-radiating object moves from one sensing area to the neighboring sensing area. We followed a circular path to keep the same distance from the sensor in each measurement. A simple visualization of the experimental pattern used in our evaluation is shown in Figure 9.

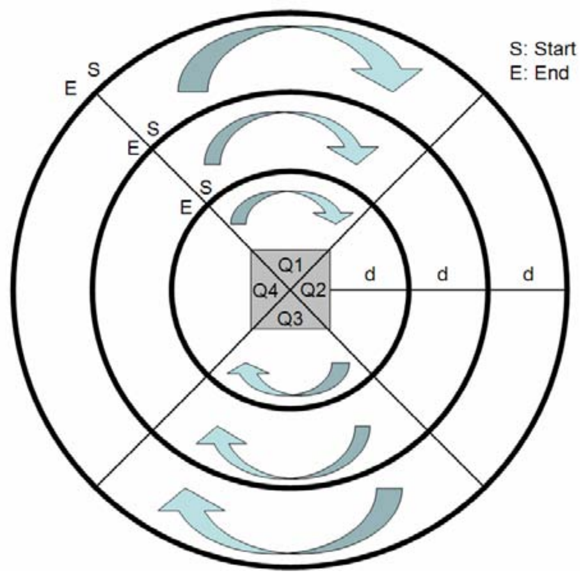

Figure 9. Circular Experimental Pattern

The MSP410 mote sensor node should be activated and connected to the computer via the MBR410 base station at the beginning of the experiments. A person walks from position S to position E at a constant speed, as shown in Figure 9. If sensing elements catch a heat source, the mote sensor node reports the detection to the base station with the quadrant information and the PIR value based on the temperature of the object.

2. Slow Speed Experiments

We decided to begin our evaluation experiments with slow-moving targets in order to understand PIR sensor behavior. We decided to walk at 0.3 m/s, which is a differentiable speed between moving and steady objects. We conducted slow speed experiments on a sunny day when there was no wind. The temperature was 18^{o}C near mote sensor nodes. One person walked in the path over the circles, which had radii of 2m, 4m, and 6m respectively. Sensor readings are given in Table 2 in Appendix. Target positions based on mote sensor readings are plotted for sensor 1 in Figure 10 as an illustration for object movement detection.

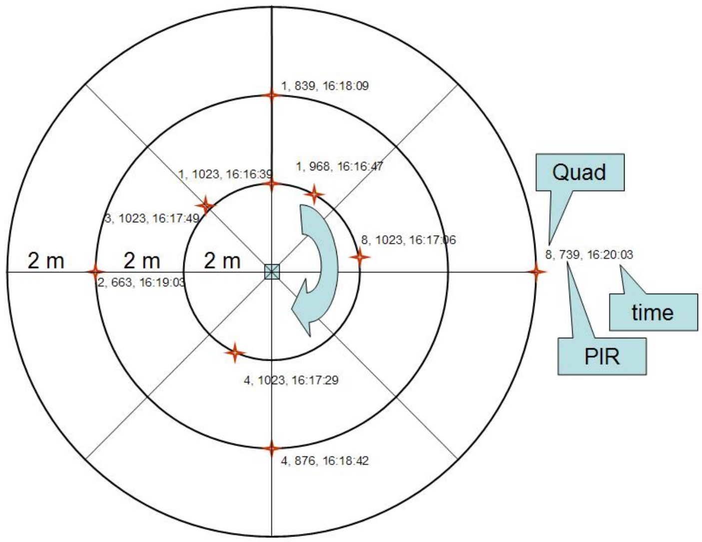

Figure 10. Target Position Plot For Sensor 1 Readings

A scatter plot of sensor readings for slow speed experiments is shown in Figure 11. As seen on the scatterplot, PIR readings dramatically decrease with distance. Although the sensor's maximum range is 15 meters, it hardly detects moving target at 6 meters. We learned through discussions with the manufacturer that the reason for range decrease is the timeout mechanism built into the detection algorithm of the MSP410 mote sensor node. The timeout mechanism built into the detection algorithm is used to reduce the number of false alarms. A timeout occurs when an object doesn't pass from one sensing area to another in a certain period of time.

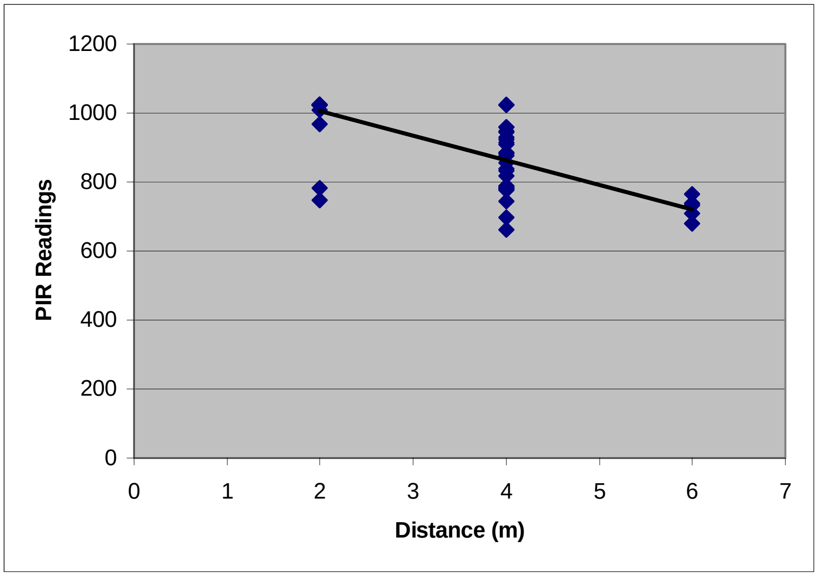

Figure 11. Slow Speed Experiments Sensor Readings Scatterplot

3. Walking Speed Experiments

We continued our experiments with a normal walking speed of 1 m/s. We followed the same walking pattern as the previous experiments. Since all sensor nodes are identical and previous measurements are similar for all sensor nodes, we randomly selected sensor node 3 for the following experiments. We completed these experiments under conditions similar to the conditions for the slow speed experiments within the same configuration. The same person followed the same pattern on a sunny day at 13^{o}C when there was no wind. The scatterplot of sensor readings for our first walking speed experiment is shown in Figure 12. Sensor readings are given in Table 3 in Appendix.

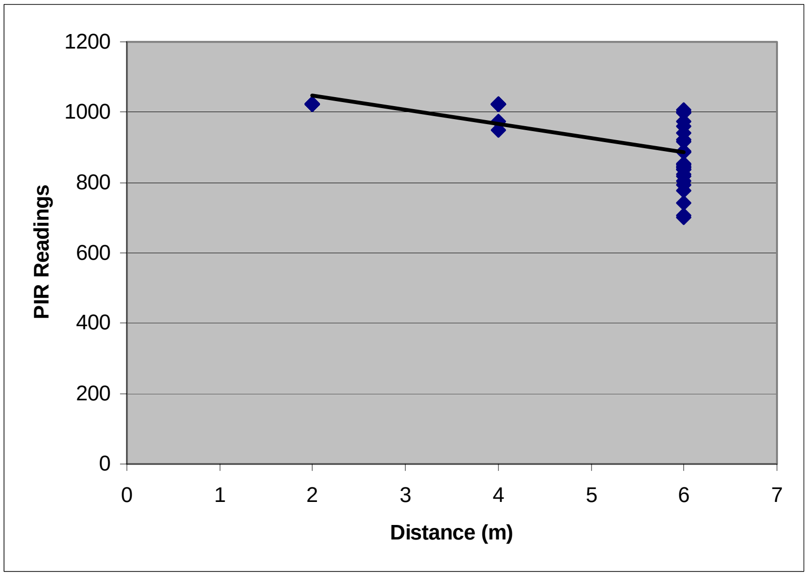

Figure 12. Walking Speed Experiment-1 Sensor Readings Scatterplot

Although The PIR readings decrease with distance, they are very close to maximum PIR value within 4 m range. It can be seen on the scatterplot that the PIR readings follow a descending trend related to the distance of the object. Since we were able to get more detection at 6 m than previous experiment, we decided to expand the distance for the following experiment.

We started the second walking speed experiment with conditions similar to the previous experiment. The temperature was 12^{o}C on a sunny day when there was no wind around the experiment area. We expanded the outer circle up to 10 m for our circular experimental pattern. The same person followed the expanded pattern for this experiment. The sensor readings for the second walking speed experiment are given in Table 4 in Appendix. The scatterplot for the sensor readings is shown in Figure 13.

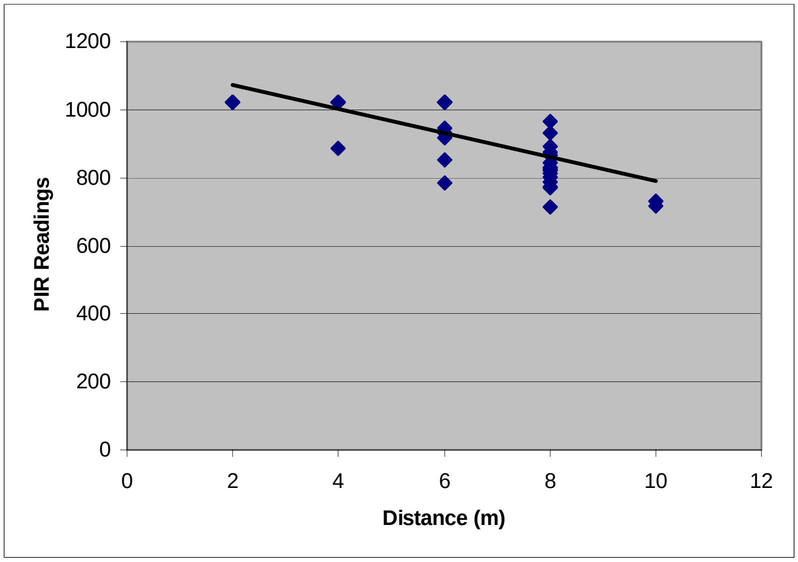

Figure 13. Walking Speed Experiment-1 Sensor Readings Scatterplot

We found a descending trend based on the distance of the moving target for this experiment. As seen on the scatterplot, the PIR readings are very close to minimum PIR value at 10 m circle.

We completed our experiments after the second walking speed experiment when we believed that we had captured enough information to develop a detection model for the MSP410 mote sensor node.

D. PIR DETECTION MODEL FOR THE MSP410 MOTE SENSOR NODE

We aimed to develop a PIR detection model for the MSP410 mote sensor node based on its PIR detection probability, given that there is a moving human in the range of the sensor node. As we discussed in previous sections, MSP410 mote sensor node PIR detection capability is a function of several parameters. We derived from our experiments that an object's speed and distance are the dominant parameters in PIR movement detection function for human movement detection. We mainly considered distance parameter while we developed our model. Our model compensates for PIR sensor detection probability in relation to an object's speed.

We decided to count each pass by a sensor's sensing element coverage area as a run. Although the sensor may have reported multiple detections in a run, we counted only one of the detections in a binary detect-or-miss fashion when there were multiple detections in a run.

We executed a total of 96 runs in our slow speed experiments, which were evenly distributed over 3 different distances. We received 31 detections over 32 runs at the 2 m circle from the sensor nodes, 25 detections over 32 runs at the 4 m circle from the sensor nodes, and 5 detections over 32 runs at the 6 m circle from the sensor nodes. The probabilities are 0.97, 0.78, and 0.16 respectively. A probability plot based on the distance for the slow speed experiments is shown in Figure 14. As seen on the chart below, PIR detection probability dramatically decreases with the distance. We can derive from the chart that the timeout mechanism is a very important factor that affects the detection probability of the MSP410 mote sensor node for slow moving humans.

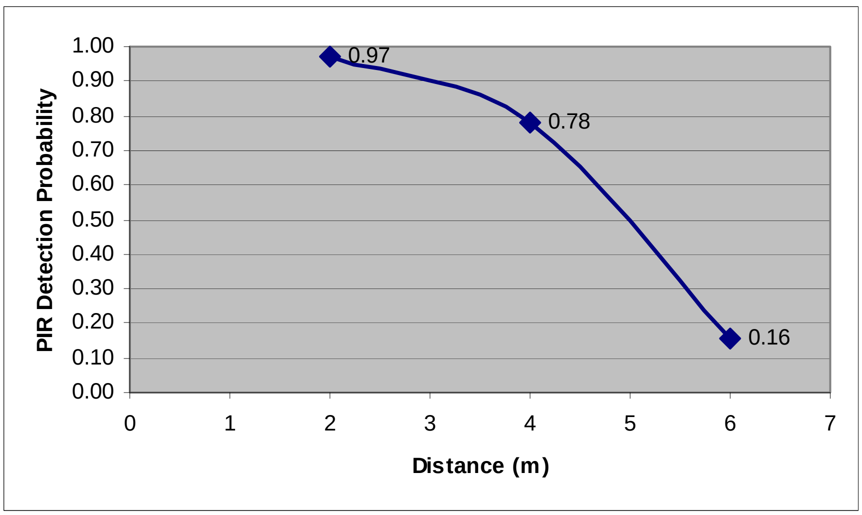

Figure 14. Slow Speed Experiments PIR Detection Probability

In our first walking speed experiment, we executed a total of 72 runs that were distributed over 3 different distances. We received 22 detections over 28 runs at the 2 m circle from the sensor node, 20 detections over 20 runs at the 4 m circle from the sensor node, and 24 detections over 24 runs at the 6 m circle from the sensor node. The probabilities are 0.79, 1.00, and 1.00 respectively. A probability plot based on distances for the first walking speed experiment is shown in Figure 15.

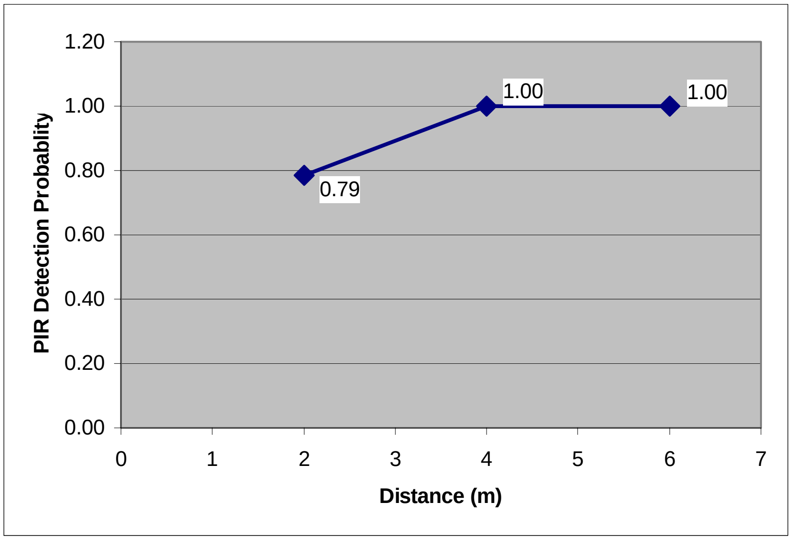

Figure 15. Walking Speed Experiment-1 PIR Detection Probability

In our second walking speed experiment, we conducted a total of 104 runs that were distributed over 5 different distances. We received 10 detections over 20 runs at the 2 m circle from the sensor node, 14 detections over 24 runs at the 4 m circle from the sensor node, 18 detections over 20 runs at the 6 m circle from the sensor node, 17 detections over 20 runs at the 8 m circle from the sensor node, and 3 detections over 20 runs at the 10 m circle from the sensor node. The probabilities are 0.50, 0.58, 0.90, 0.85, and 0.15 respectively. A probability plot based on distances for the second walking speed experiment is shown in Figure 16.

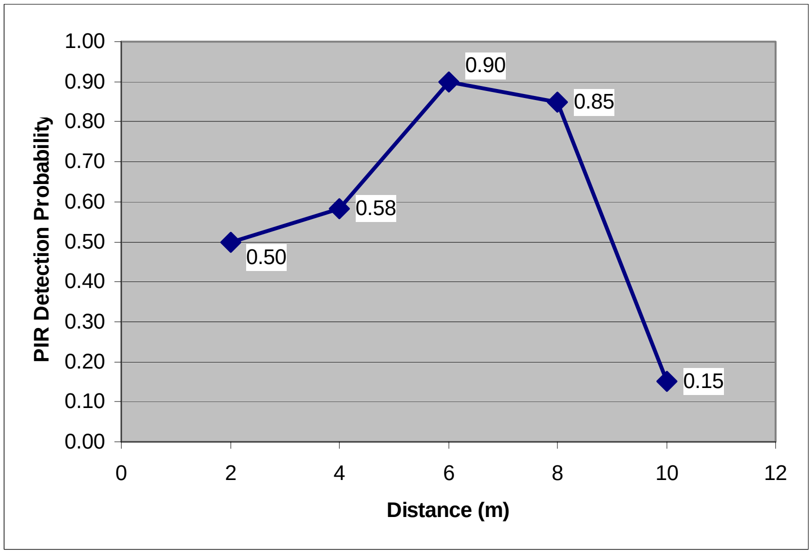

Figure 16. Walking Speed Experiment-2 PIR Detection Probability

In our walking speed experiments we conducted a total of 172 runs that were distributed over 5 different distances. We received 32 detections over 48 runs at the 2 m circle from the sensor node, 34 detections over 40 runs at the 4 m circle from the sensor node, 42 detections over 44 runs at the 6 m circle from the sensor node, 17 detections over 20 runs at the 8 m circle from the sensor node, and 3 detections over 20 runs at the 10 m circle from the sensor node. The probabilities are 0.67, 0.85, 0.95, 0.85, and 0.15 respectively. A probability plot based on distances for the walking speed experiments is shown in Figure 17. As seen on the chart below, PIR detection probability dramatically decreases after 8 meters.

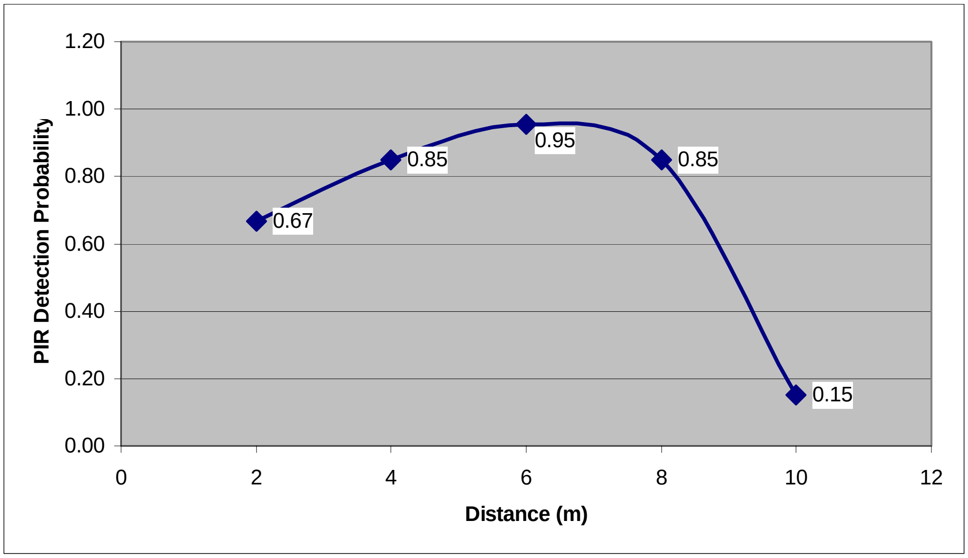

Figure 17. Walking Speed Experiments PIR Detection Probability

We can develop our PIR detection model for the MSP410 mote sensor nodes based on observed probabilities from our experiments. In order to develop a good PIR detection model, we may assume that:

- The intruder is unaware of the sensing capabilities of the MSP410 mote sensor nodes
- The intruder is unaware of the existence of the sensors in the monitored area
- The intruder enters the monitored area out of sensing range of a sensor node
- The intruder isn't wearing any special equipment to lower his/her body temperature

Since the intruder needs to enter the area out of the sensing range of a sensor node, he/she can pass the sensor without being detected if and only if he/she is not detected at any distance to the sensor on his/her path in the sensing area of a sensor node. We can find the probability of detecting an intruder by using the complement and multiplication rules of probability based on our observations. We can say that the probability of not being detected by a sensor node in the sensor's sensing area is the product of the probabilities of not being detected at any distance throughout the path of the intruder. We can formulize an estimator for calculating the probability of detecting an intruder.

Estimator 1:

If $P(I)$ is the cumulative probability of detecting an intruder in the sensing area of a sensor node, and $P_i(I)$ is the observed probability of detecting an intruder at distance "*i*" meters, then

$$P(I) = \left[1 - \left(\prod_{i=0}^{n}(1 - P_i(I))\right)\right] \qquad (1)$$

We observed from our experiments that the detection range increases as the speed of the object increases. We can calculate cumulative detection probabilities using walking speed detection probabilities according to observed relations of slow speed and walking speed detection distances. Cumulative PIR detection probabilities calculated by using Estimator (1) are shown in Figure 18.

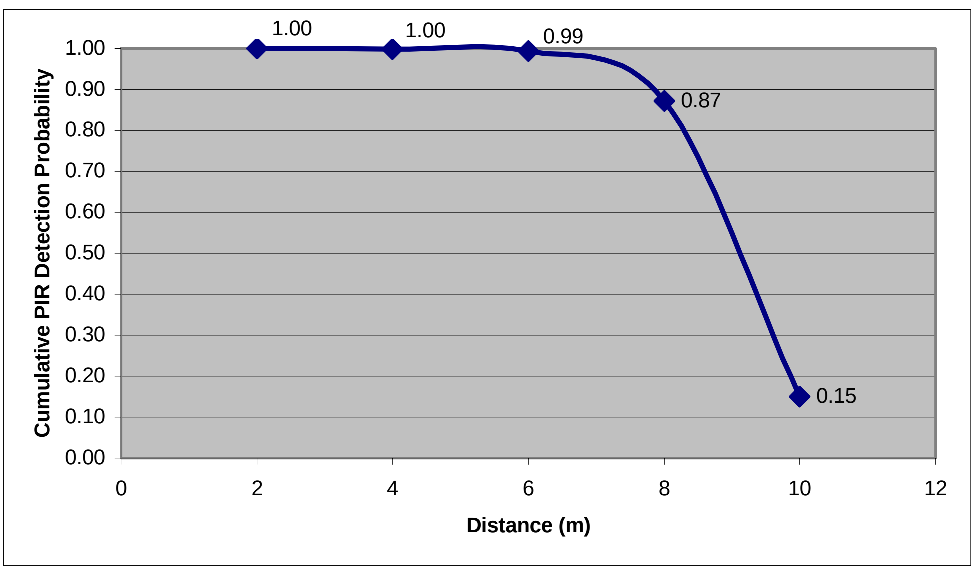

Figure 18. Cumulative PIR Detection Probability Chart

We can accept maximum range for our sensor nodes as 10 m, which is the lower boundary for its maximum sensitivity level from Table 1. As we saw in Figure 18, MSP410 mote sensor nodes are capable of detecting human movement at a distance up to 8 m with high cumulative probabilities. We can divide the sensor's coverage area into two portions based on its detection probabilities. The high probability region goes up to 8 meters, and the low probability region continues up to the sensor's maximum range of 10 meters. We can assume reliable PIR movement detection in the high probability region in good environmental conditions.

The PIR detection model for MSP410 mote sensor nodes is shown in Figure 19. We can develop efficient deployment strategies for human movement detection applications by using our PIR detection model. Distance parameters can be adjusted accordingly in order to meet application requirements for efficient deployment strategies.

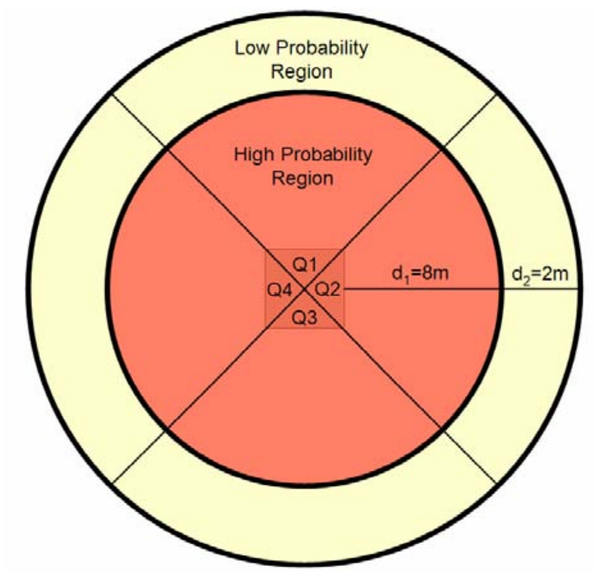

Figure 19. PIR Detection Model for MSP410 Mote Sensor Nodes

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IV. BORDER MONITORING BASED ON A NOVEL PIR DETECTION MODEL

In this chapter, we will propose an efficient strategy, based on the new PIR model presented in Chapter III, for placing MSP410 mote sensor nodes in a border-monitoring scenario. The proposed placement strategy assumes a static deployment of mote sensors. Therefore, we will briefly compare the static and random methods of sensor deployment. Several intelligent sensor placement strategies have been suggested in the WSN literature, one of which in particular has targeted the border monitoring application. We will continue by reviewing these prior approaches. Finally, we will present our strategy and discuss its strengths and its weaknesses.

A. WIRELESS SENSOR DEPLOYMENT METHODS

Wireless sensor nodes can be deployed in different ways based on application needs, terrain, environmental conditions, and other circumstances. The two main wireless sensor deployment scenarios are the random deployment method and the static deployment method, depending on whether the positions of the sensor nodes can be adjusted after the initial deployment [10].

1. Random Deployment Method

The Random deployment method is an easy sensor deployment method that can be used when the absolute positions of the sensors are not important for the application. Wireless sensor nodes can be deployed using this method when:

- The wireless sensor network has a large number of sensor nodes.
- The terrain is not appropriate for the static deployment method.
- The wireless sensor nodes have the positioning capability for rearrangement after deployment.
- The application requires random sensor positions.

The random deployment method requires advanced wireless sensor nodes, which have positioning capability, for certain applications. Wireless sensor nodes can be deployed from various platforms using the random deployment method. This method is much faster than static deployment because of the initial deployment times. The following methods can be used for random deployment:

- Dropping from a vehicle
- Dropping from a plane
- Launching with a missile
- Firing with a gun or torpedo

2. Static Deployment Method

A person or a machine must place the wireless sensor nodes in previously planned positions for this placement method. Although the static deployment method is much slower than the random deployment method, it doesn't require advanced sensors for repositioning and position adjustments after the initial deployment. The static deployment method is applicable when:

- The wireless sensor network has small number of wireless sensor nodes.
- The terrain is appropriate for the static deployment method.
- The application requires fixed sensor positions.
- The application requires fixed distances between wireless sensor nodes.
- The wireless sensor nodes aren't capable of position adjustments.

Since the static deployment method is used when position adjustments aren't needed, wireless sensor nodes can be deployed by a person, deployed by a robot, or installed at the factory for performance monitoring on vehicles including ships, airplanes, trucks, etc.

B. PRIOR PROPOSALS OF SENSOR PLACEMENT STRATEGIES

In this section, we will review three existing sensor placement strategies. While the first two are developed for the problem of area coverage, they are included here to illustrate the broad issues related to designing an intelligent sensor placement strategy. The third strategy specifically targets the border-monitoring scenario for which our strategy is intended.

Before discussing the individual schemes, we will first introduce a common performance metric used in the first two strategies. The efficiency of the sensor placement is one of the important factors in wireless sensor placement strategy. Since higher efficiency is desired in most cases, the desired high efficiency can be achieved by minimizing the number of wireless sensor nodes required to cover a monitoring area. First, we need to have a sensing model for a wireless sensor node in order to design and maximize the efficiency of a sensor placement strategy.

For our discussion, we will use a binary sensing model that is commonly used in wireless sensor placement studies. The binary sensing model for a wireless sensor node located at position x_0 where it has the capability S of sensing for a given location x is defined in [10] as

$$S(x_0, x) = \begin{cases} 1 & \text{if } d\left(x_0, x\right) \leq R_s \\ 0 & \text{if } d\left(x_0, x\right) > R_s \end{cases} \tag{2}$$

where R_s is the sensing radius, and the distance metric $d\left(\cdot,\cdot\right)$ is the Euclidean distance.

Two types of sensor coverage are considered in wireless sensor placement strategies. These are non-overlapped and overlapped sensor coverage and examples of both are shown in Figure 20. We will use the overlapped sensor coverage method in order to have no uncovered areas in the monitored region.

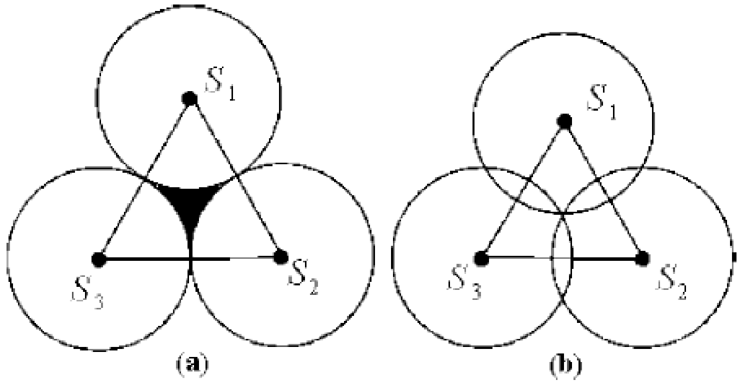

Figure 20. Nonoverlapped and Overlapped Sensor Coverage Areas (from Ref. [11])

Since we are using the overlapped sensor coverage method, we need to define sensing efficiency to adjust the degree of overlapping. Sensing efficiency is described in [10] by using sensing efficiency ratio ρ as the ratio of two areas

$$\rho = \frac{A_{sep}}{A_{col}} \qquad (3)$$

where A_{sep} is the sum of the area covered by each individual sensor node, and A_{col} is the area actually covered by all the sensor nodes. It is clearly seen from (3) that $\rho \geq 1$. According to this definition, the closer the efficiency ratio gets to 1, the higher the efficiency becomes.

We can define the sensing efficiency, ε, by using (3). The new efficiency parameter can be written as

$$\varepsilon = \frac{1}{\rho} x100 . \qquad (4)$$

The wireless sensor placement strategy becomes more efficient as ε gets closer to 100%. The problem of finding the most efficient coverage using binary sensing model is known as circle covering problem, in which a number of equivalent circles are placed in a field to completely cover the field [10]. It is shown in [12] that a hexagonal circle placement in which neighboring circles are $\sqrt{3}\,r$ apart from each other is the most efficient placement strategy.

Since we are trying to minimize overlapping sensor coverage in order to increase efficiency of the wireless sensor placement strategy, we need to find such distances between neighboring sensor nodes that at most two sensor nodes overlap at any given point in the monitored area. We can show this requirement as

$$A_{1..n}(s_1 \cap s_2 \cap .. \cap s_n) = \varnothing \quad (n > 2) \tag{5}$$

where s_1 denotes a sensor node, and $s_2, .., s_n$ denote its neighbors.

1. Hexagon Lattice Strategy

The circle covering problem is solved in [12] to state that in order to cover the maximum area with the minimum number of circles, each circle needs to be $\sqrt{3}r$ apart from each other. This will form a hexagonal pattern. This hexagonal pattern is called hexagon lattice in WSN literature. Since wireless sensor nodes have circular sensing coverage areas, we can use the hexagon lattice to place our wireless sensor nodes in order to achieve the highest efficiency in many circumstances. Finding the optimum wireless sensor placement strategy mainly depends on the application and the shape of the surveillance area. Because of that, it may not be appropriate to use the hexagon lattice in all scenarios. An illustration of wireless sensor placement using the hexagon lattice is shown in Figure 21.

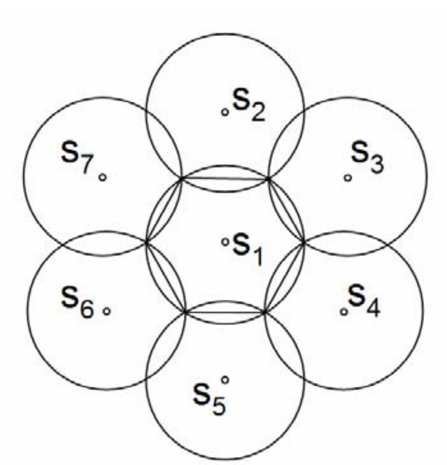

Figure 21. Wireless Sensor Placement Using the Hexagon Lattice

As seen in Figure 21, each sensor node contributes to the total coverage area at least as much as the area of a hexagon formed by the intersecting points on the inner circle's perimeter based on its location in the monitored area. Outer sensor nodes may contribute more sensing coverage than the inner sensor nodes. The lowest efficiency ratio is calculated as $\rho = 2\pi/\sqrt{27} \approx 1.21$ in this placement strategy [10]. Efficiency, ε, can be found to be 82.64% by using Equation (4).

2. Square Lattice Strategy

Another possible wireless placement strategy that will satisfy equation (5) and increase the efficiency is the square lattice placement method. Although the square lattice deployment is not as efficient as the hexagon lattice deployment, it may be better to use the square lattice deployment method in rectangular fields to minimize the number of sensors that need to be placed. Each sensor node is placed $\sqrt{2}\,r$ apart from its vertical and horizontal neighbors, while the diagonal neighbors are placed *2r* apart from each other in this lattice deployment. A visualization of the wireless sensor placement using the square lattice deployment is shown in Figure 22.

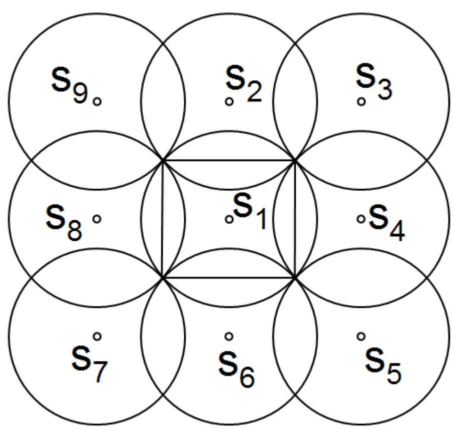

Figure 22. Wireless Sensor Placement Using The Square Lattice

As seen in Figure 22, each sensor node contributes to the total coverage area at least as much as the area of a square formed by the intersecting points on the inner circle's perimeter based on its location in the monitored area. The outer sensor nodes may contribute more sensing coverage than the inner sensor nodes. The lowest efficiency ratio is calculated as $\rho = \pi/2 \approx 1.57$ in this placement strategy [10]. Efficiency, ε, can be found to be 63.7% by using Equation (4).

3. Barrier Coverage Strategy

The barrier coverage strategy is aimed at reducing the number of sensors used to cover an area within an intended level of sensing regions. Because of its design philosophy, this strategy doesn't provide full coverage in a deployment area. A region is said to be k-barrier covered if every path in the region intersects with at least k number of sensors' sensing area [13]. An intruder needs to pass through at least k number of stealthy sensors' coverage areas in order to reach a protected region.

Both deployment methods, random and static deployment, can be used to achieve the desired level of coverage in this strategy. An illustration of 3-barrier coverage is shown in Figure 23. Since this strategy contains uncovered regions, it is prone to coverage holes when one sensor from each level of sensing region malfunctions.

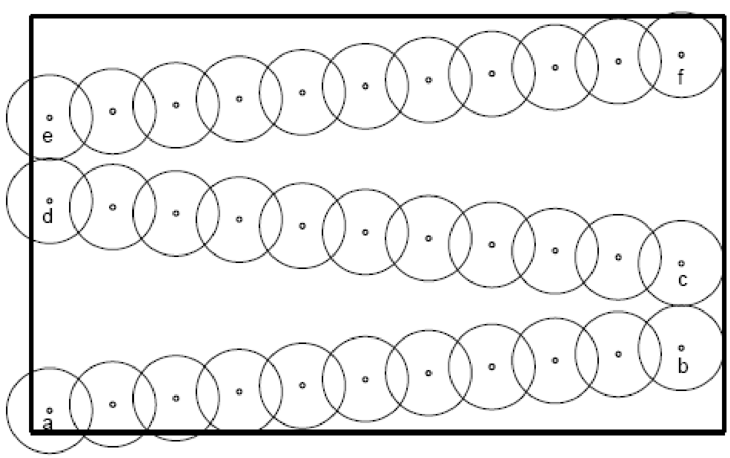

Figure 23. 3-Barrier Coverage with Wireless Sensors (from Ref. [13])

C. A STRATEGY FOR BORDER MONITORING WITH MSP410 MOTES

Crossbow recommends two types of wireless sensor placement strategy for its MSP410 mote security system. These deployment strategies are deployment for perimeter monitoring and deployment for dense grid monitoring.

The perimeter monitoring deployment method is shown in Figure 24. This method may be useful for monitoring houses when using a small number of wireless sensor nodes.

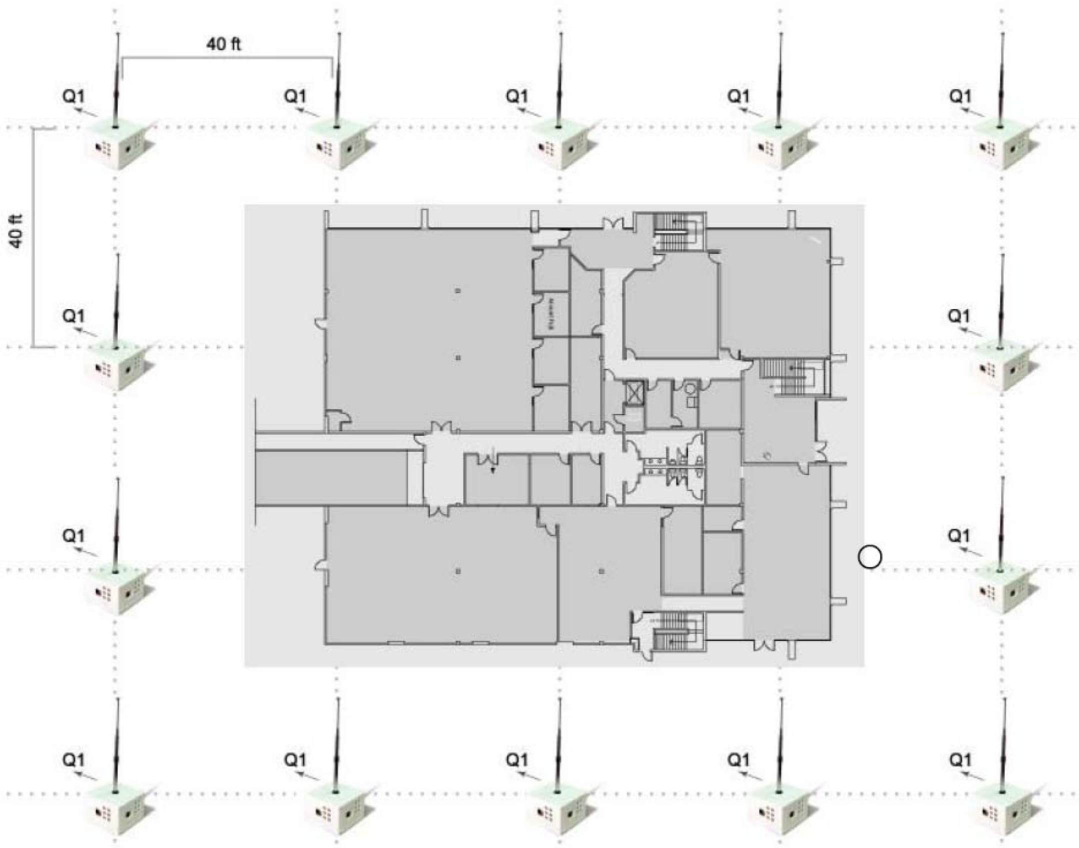

Figure 24. Perimeter Monitoring Deployment for MSP410 Mote Security System (from Ref. [5])

The other recommended wireless sensor placement strategy, deployment for dense grid monitoring, is shown in Figure 25. This strategy uses hexagon lattice deployment method. It is used for monitoring an entire field when large numbers of wireless sensor nodes are available.

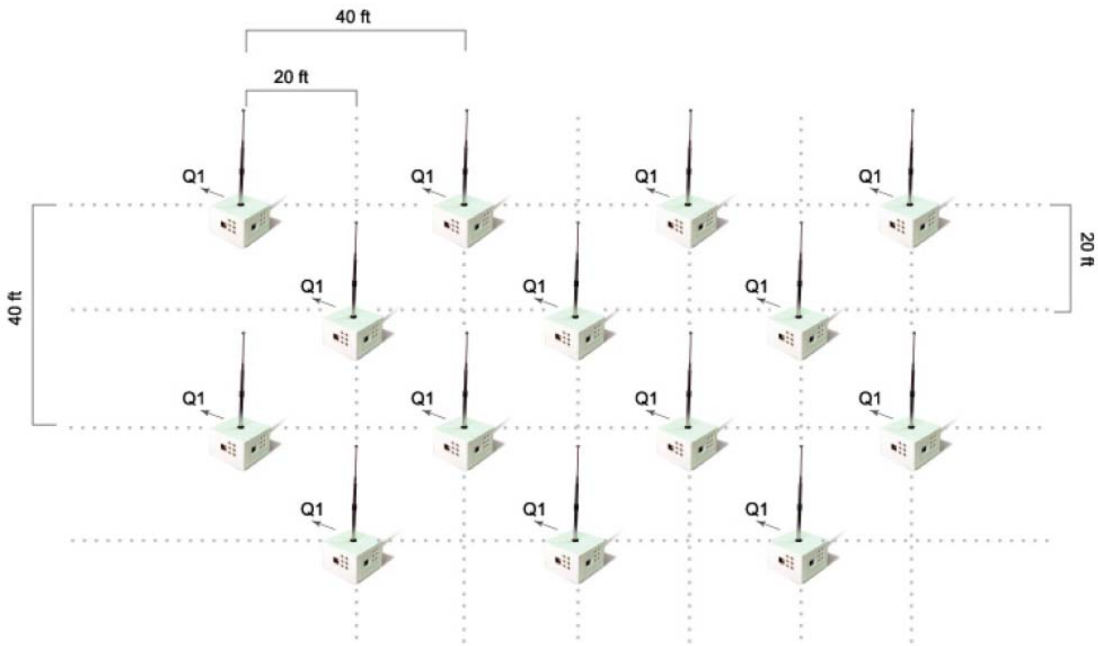

Figure 25. Dense Grid Monitoring Deployment for MSP410 Mote Security System (from Ref. [5])

We will develop a wireless sensor placement strategy using the PIR detection model for MSP410 mote sensor node. There are two different movement detection probabilities, $P_{hi}(I)$ and $P_{lo}(I)$, in the PIR detection model. We want to have high probability regions on the borders of the field that is being monitored. We know from previous sections that the most efficient placement strategy is achieved using the hexagon lattice. We will use a special subset of the hexagon lattice, a triangular lattice, in our wireless sensor placement strategy.

We need to adjust the distance between neighboring wireless sensor nodes in order to increase the detection probability in low probability regions of the PIR detection model. The probability of overlapping two low probability regions, $P_{lo}(I)$, is calculated as

$$P_{ov}(I) = 1 - \left(1 - P_{lo}(I)\right)^2 \quad (6)$$

It is clear from Equation (6) that $P_{ov}(I) \geq P_{lo}(I)$. A visualization of overlapped low probability regions is shown in Figure 25. We can place MSP410 mote sensor nodes 18 m apart from each other so that the 2 m low probability regions overlap in order to increase the detection probability.

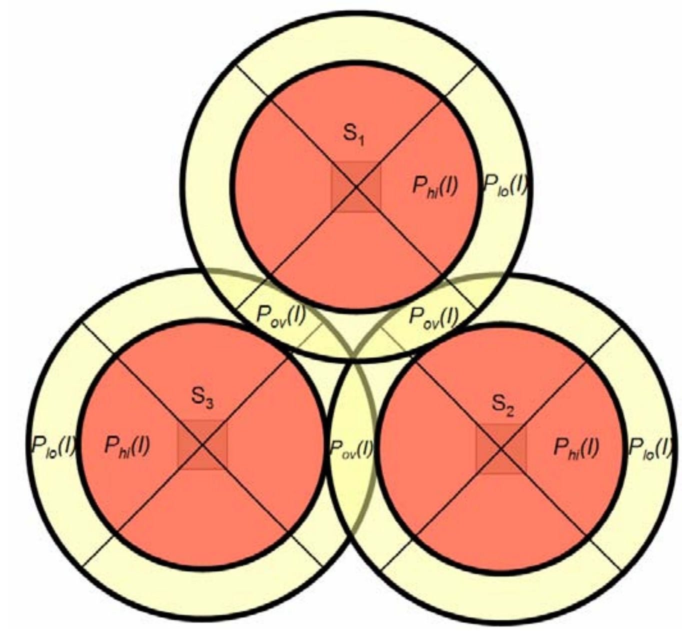

Figure 26. Overlapped Placement Using PIR Detection Model

Although orientations of MSP410 mote sensor nodes are important, they aren't considered in Figure 26. We will consider orientations in actual placement. Since the MSP410 mote sensor node divides its sensing coverage area into four 90-degree sensing regions, we can use this property to locate an intruder if the intruder is in the field that is being monitored. In order to make an accurate decision we will define an early warning section for our wireless sensor placement strategy.

Placing all the wireless sensor nodes inside the area that is being monitored in order to cover the area using minimum number of wireless sensor nodes is a common approach in the WSN literature. We want to also place the outer wireless sensor nodes on the perimeter of the monitoring area to benefit from the four 90-degree sensing regions of the MSP410 mote sensor nodes. By placing an MSP410 mote sensor node on the perimeter of the field that is being monitored in such a way that two of its 90-degree sensing regions look outward and the other two look inward, we can make accurate decisions about the location of an intruder when a sensor node reports a PIR detection. We will call the sum of outward-looking sensing areas the early warning area. We will concentrate on the early warning area for a PIR detection event before a suspicious target moves into our monitoring area.

We will place a second row of wireless sensor nodes behind the first row in order to create a border belt that has high detection probability to prevent sensing shortages caused by sensor node failures. The wireless sensor placement strategy for border monitoring scenarios using the PIR detection model developed for the MSP410 mote sensor nodes is shown in Figure 27.

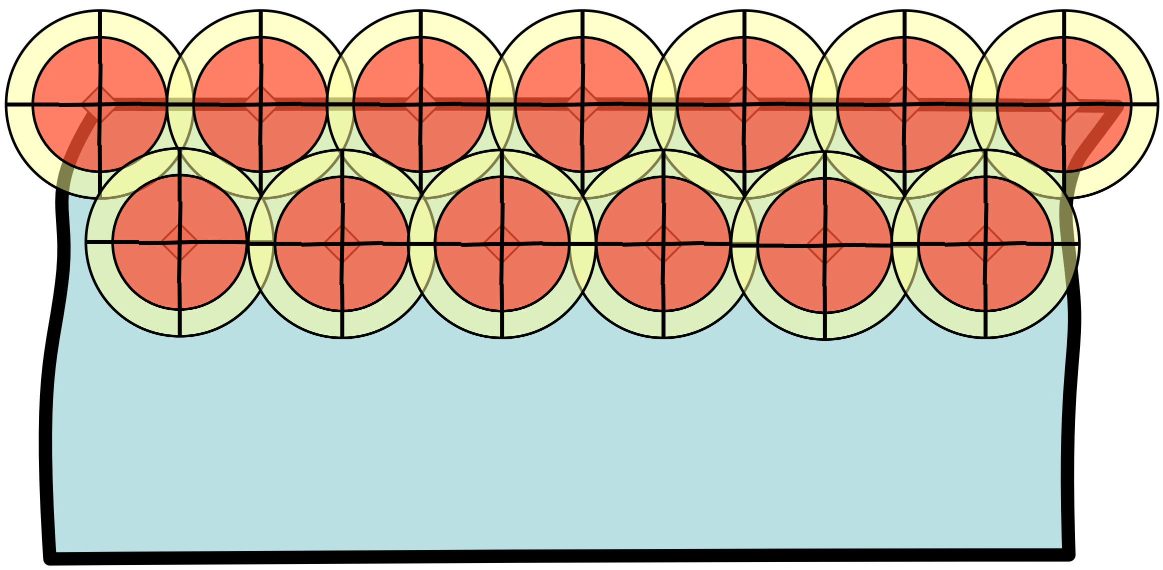

Figure 27. Wireless Sensor Placement Strategy for Border Monitoring Scenarios

The blue area on Figure 27 shows a portion of a monitored area. The first level of wireless sensor nodes is placed border, and the second level of wireless sensor nodes placed behind it acts to strengthen the sensor placement strategy in order to prevent gaps in the sensor placement strategy due to sensor failures. The outer side of the wireless sensor nodes placed in the first row is used as an early warning area that helps us to gain time in order to take action against intruders. As seen on Figure 27, the sum of high probability regions and intersecting areas creates a continuous belt through the border of the monitored field. The distance between neighboring sensor nodes can be closer than the proposed placement to increase the detection probability of the overlapping regions.

The current version of the MoteView™ software doesn't support different orientations of the MSP410 mote sensor nodes. The second row of wireless sensor nodes can be angled differently from the first row of wireless sensor nodes in order to make accurate decisions about an intruder's position. The MSP410 mote sensor nodes can be used in different orientations by updating the software to keep track of the detailed orientation information for the MSP410 mote sensor nodes.

1. Strengths of the Strategy

This strategy is intended to increase the PIR detection probability of the MSP410 mote sensor nodes. It provides high probability PIR detection capability in desired areas such as borders and choke points. The strategy supports continuous border coverage against sensor failures. The early warning region makes it possible to detect suspicious activity before it reaches the perimeter of the field that is being monitored and focuses the attention on that region. The outer row of sensors enables the discrimination of an object's location relative to the perimeter of the monitored field.

2. Weaknesses of the Strategy

This strategy requires static deployment of sensors in order to achieve its maximum efficiency. It uses more wireless sensors than the k-barrier coverage strategy. Sensor density may adversely affect the network performance.

V. CONCLUSION

A. CONCLUSIONS

We have investigated the Crossbow MSP410 mote sensor node's PIR detection behavior in a series of experiments for surveillance and intrusion detection applications. It has been demonstrated that a MSP410 mote sensor node's detection behavior is a function of an object's speed and distance from the sensor node. We have developed a PIR detection model for the MSP410 mote sensor nodes based on the PIR detection probabilities observed in the experiments. We have suggested that the range of the high probability region can be adjusted in order to customize the new PIR detection model according to requirements of the application.

We have designed a wireless sensor placement strategy using the new PIR detection model for border monitoring scenarios in surveillance and intrusion detection applications with MSP410 mote sensor nodes. The sensor placement strategy creates an early warning area to decrease the response time for investigation of an alarm. The strategy helps to discriminate the relative location of a target when it is detected in the monitoring field by using the independent sensing sections of the MSP410 mote sensor nodes. The placement strategy creates a high PIR detection probability belt using multiple levels of sensor nodes. Using multiple levels of sensor nodes increases the robustness of the WSN, particularly in respect to sensor failures.

B. RELATED FUTURE WORK

Since the current version of MOTEVIEW software requires all the MSP410 mote sensor nodes use the same orientation, we can't use sensor nodes with different orientations in order to estimate the accurate location of the target. It is possible to use the MSP410 mote sensor nodes in specially oriented deployments for target localization and tracking scenarios in field monitoring applications. The MOTEVIEW software can be updated in order to allow different orientations of mote sensor nodes by keeping detailed orientation information for each mote sensor node.

The adjustable high probability range of the new PIR detection model can be used as a tool to find the optimum placement for the sensor nodes according to the requirements of the application. Therefore, the new PIR detection model for the MSP410 mote sensor nodes can be simulated to find the best placement strategy for large wireless sensor networks in different monitoring scenarios.

APPENDIX. THE MSP410 MOTE SENSOR READINGS

A. THE SLOW SPEED EXPERIMENTS SENSOR READINGS

The sensor readings from the slow speed experiments are given in Table 2.

Sensor	Quad	PIR	Distance	Time
1	1	1023	2 m	16:16:39
1	1	968	2 m	16:16:47
1	8	1023	2 m	16:17:06
1	4	1023	2 m	16:17:29
1	3	1023	2 m	16:17:49
1	1	839	4 m	16:18:09
1	4	876	4 m	16:18:42
1	2	663	4 m	16:19:03
1	8	739	6 m	16:20:03
2	8	1023	2 m	16:25:21
2	4	1023	2 m	16:25:39
2	2	1023	2 m	16:25:49
2	8	959	4 m	16:26:19
2	8	959	4 m	16:26:20
2	4	778	4 m	16:26:31
2	2	1023	4 m	16:26:55
2	1	945	4 m	16:27:20
3	1	1023	2 m	16:31:53
3	12	1023	2 m	16:32:04
3	6	1023	2 m	16:32:16
3	2	1023	2 m	16:32:24
3	8	783	4 m	16:32:53
3	8	696	4 m	16:32:55
3	8	743	4 m	16:33:03

Sensor	Quad	PIR	Distance	Time
3	4	781	4 m	16:33:14
3	6	787	4 m	16:33:24
3	3	885	4 m	16:33:38
4	1	1023	2 m	16:38:29
4	12	1023	2 m	16:38:40
4	4	1023	2 m	16:38:47
4	2	1023	2 m	16:38:55
4	1	1023	2 m	16:39:12
4	4	781	4 m	16:39:36
4	2	787	4 m	16:39:57
4	4	709	6 m	16:40:44
5	1	782	2 m	16:44:29
5	8	1023	2 m	16:44:41
5	4	746	2 m	16:44:51
5	2	1023	2 m	16:44:59
5	1	1023	2 m	16:45:07
5	1	923	4 m	16:45:16
5	4	831	4 m	16:45:44
5	2	910	4 m	16:46:06
5	2	680	6 m	16:47:06
5	1	731	6 m	16:47:36
6	1	1023	2 m	16:50:02
6	8	1023	2 m	16:50:12
6	6	1023	2 m	16:50:24
6	2	1023	2 m	16:50:30
6	1	947	4 m	16:50:51
6	4	930	4 m	16:51:11
6	2	857	4 m	16:51:27

Sensor	Quad	PIR	Distance	Time
6	8	765	6 m	16:51:57
7	1	1023	2 m	16:56:54
7	8	1023	2 m	16:57:05
7	4	1023	2 m	16:57:12
7	2	1023	2 m	16:57:19
7	1	1009	2 m	16:57:28
7	6	883	4 m	16:58:02
7	3	1023	4 m	16:58:13
8	1	1023	2 m	17:02:53
8	8	1023	2 m	17:03:00
8	4	1023	2 m	17:03:11
8	2	1023	2 m	17:03:18
8	1	776	4 m	17:03:32
8	4	817	4 m	17:03:52
8	6	915	4 m	17:04:00
8	2	1023	4 m	17:04:08

Table 2. The Sensor Readings from the Slow Speed Experiments

B. THE WALKING SPEED EXPERIMENTS SENSOR READINGS

The sensor readings from the first walking speed experiments are given in Table 3.

Sensor	Quad	PIR	Distance	Time
3	1	1023	2 m	14:57:02
3	8	1023	2 m	14:57:09
3	4	1023	2 m	14:57:14
3	3	1023	2 m	14:57:21
3	8	1023	2 m	14:57:28
3	4	1023	2 m	14:57:34

Sensor	Quad	PIR	Distance	Time
3	2	1023	2 m	14:57:40
3	9	1023	2 m	14:57:46
3	4	1023	2 m	14:57:52
3	2	1023	2 m	14:57:59
3	1	1023	2 m	14:58:05
3	12	1023	2 m	14:58:10
3	6	1023	2 m	14:58:17
3	1	1023	2 m	14:58:23
3	12	1023	2 m	14:58:30
3	2	1023	2 m	14:58:36
3	1	1023	2 m	14:58:42
3	12	1023	2 m	14:58:47
3	2	1023	2 m	14:58:54
3	1	1023	2 m	14:59:00
3	12	1023	2 m	14:59:06
3	2	1023	2 m	14:59:12
3	1	1023	4 m	15:00:02
3	9	975	4 m	15:00:08
3	12	949	4 m	15:00:14
3	6	1023	4 m	15:00:21
3	2	1023	4 m	15:00:28
3	1	1023	4 m	15:00:35
3	8	1023	4 m	15:00:42
3	4	1023	4 m	15:00:49
3	2	1023	4 m	15:00:56
3	1	1023	4 m	15:01:03
3	8	1023	4 m	15:01:11
3	4	1023	4 m	15:01:17

Sensor	Quad	PIR	Distance	Time
3	2	1023	4 m	15:01:24
3	1	1023	4 m	15:01:31
3	8	1023	4 m	15:01:38
3	4	1023	4 m	15:01:45
3	2	1023	4 m	15:01:52
3	1	1023	4 m	15:01:59
3	8	1023	4 m	15:02:06
3	4	1023	4 m	15:02:13
3	2	1023	4 m	15:02:20
3	1	805	6 m	15:03:07
3	8	942	6 m	15:03:19
3	6	974	6 m	15:03:30
3	2	837	6 m	15:03:38
3	9	743	6 m	15:03:48
3	8	999	6 m	15:03:56
3	4	793	6 m	15:04:04
3	2	824	6 m	15:04:15
3	1	845	6 m	15:04:23
3	8	707	6 m	15:04:35
3	4	851	6 m	15:04:44
3	2	819	6 m	15:04:52
3	9	776	6 m	15:05:02
3	8	959	6 m	15:05:10
3	6	917	6 m	15:05:21
3	2	842	6 m	15:05:29
3	1	855	6 m	15:05:36
3	8	702	6 m	15:05:48
3	6	886	6 m	15:05:57

Sensor	Quad	PIR	Distance	Time
3	2	1007	6 m	15:06:04
3	9	837	6 m	15:06:15
3	8	921	6 m	15:06:22
3	4	890	6 m	15:06:30
3	2	1002	6 m	15:06:38

Table 3. The Sensor Readings from the First Walking Speed Experiments

The sensor readings from the second walking speed experiments are given in Table 4.

Sensor	Quad	PIR	Distance	Time
3	3	1023	2 m	15:19:01
3	4	1023	2 m	15:19:07
3	1	1023	2 m	15:19:13
3	4	1023	2 m	15:19:18
3	1	1023	2 m	15:19:24
3	4	1023	2 m	15:19:29
3	1	1023	2 m	15:19:35
3	6	1023	2 m	15:19:41
3	9	1023	2 m	15:19:46
3	2	1023	2 m	15:19:52
3	1	1023	4 m	15:21:01
3	8	1023	4 m	15:21:08
3	2	1023	4 m	15:21:14
3	1	1023	4 m	15:21:21
3	12	887	4 m	15:21:27
3	2	1023	4 m	15:21:33
3	9	1023	4 m	15:21:39

Sensor	Quad	PIR	Distance	Time
3	4	1023	4 m	15:21:46
3	2	1023	4 m	15:21:52
3	8	1023	4 m	15:21:58
3	4	1023	4 m	15:22:04
3	1	1023	4 m	15:22:11
3	8	1023	4 m	15:22:17
3	2	1023	4 m	15:22:23
3	1	1023	6 m	15:24:01
3	8	1023	6 m	15:24:08
3	4	1023	6 m	15:24:15
3	2	1023	6 m	15:24:22
3	1	1023	6 m	15:24:28
3	8	854	6 m	15:24:35
3	6	1023	6 m	15:24:42
3	1	1023	6 m	15:24:48
3	8	1023	6 m	15:24:55
3	4	933	6 m	15:25:02
3	2	1023	6 m	15:25:08
3	9	945	6 m	15:25:15
3	8	784	6 m	15:25:21
3	6	1023	6 m	15:25:28
3	1	1023	6 m	15:25:35
3	8	1023	6 m	15:25:42
3	4	918	6 m	15:25:49
3	2	1023	6 m	15:25:55
3	1	813	8 m	15:27:04
3	8	824	8 m	15:27:12
3	6	775	8 m	15:27:19

Sensor	Quad	PIR	Distance	Time
3	2	932	8 m	15:27:27
3	1	770	8 m	15:27:35
3	2	967	8 m	15:27:54
3	1	831	8 m	15:28:02
3	8	802	8 m	15:28:10
3	4	714	8 m	15:28:19
3	2	893	8 m	15:28:27
3	1	821	8 m	15:28:35
3	8	874	8 m	15:28:42
3	2	868	8 m	15:28:53
3	1	843	8 m	15:29:01
3	8	829	8 m	15:29:09
3	4	787	8 m	15:29:18
3	2	868	8 m	15:29:25
3	2	731	10 m	15:31:35
3	1	730	10 m	15:33:26
3	2	717	10 m	15:33:56

Table 4. The Sensor Readings from the Second Walking Speed Experiments

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